



Software Diversification for WebAssembly

JAVIER CABRERA-ARTEAGA

Doctoral Thesis in Computer Science
Supervised by
Benoit Baudry and Martin Monperrus

Stockholm, Sweden, 2023

KTH Royal Institute of Technology
School of Electrical Engineering and Computer Science
Division of Software and Computer Systems
SE-10044 Stockholm
Sweden

TRITA-EECS-AVL-2020:4
ISBN 100-

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges
till offentlig granskning för avläggande av Teknologie doktorexamen i elektroteknik
i .

© Javier Cabrera-Arteaga , date

Tryck: Universitetsservice US AB

Abstract

WebAssembly has become the fourth officially recognized web language, allowing web browsers to adapt native applications for Web. Moreover, WebAssembly has developed into a critical component of backend scenarios such as edge computing and cloud computing. Nowadays, WebAssembly is used in a wide range of applications, including web browsers, blockchain, and cloud computing. While security was a primary focus in its design, WebAssembly remains vulnerable to attacks, including side-channels and memory corruption. In addition, WebAssembly has been exploited to transport malware, especially in instances of browser cryptojacking. Remarkably, the predictability of the WebAssembly ecosystem, including its users and the programs it hosts, is exceedingly high. This predictability can exacerbate the impact of a vulnerability within these ecosystems. For example, a flaw in a web browser, instigated by a faulty WebAssembly program, could potentially affect millions of users.

This thesis aims to enhance the security of the WebAssembly ecosystem through the introduction of methods and tools for Software Diversification. Software Diversification is a strategy designed to augment the cost of exploitation by rendering the software less predictable. By automatically generating numerous variants of a program, we can decrease predictability within ecosystems. These variants harden observable properties typically utilized to carry out attacks. For instance, we can generate variants of a program with diverse memory layouts and control-flow graphs, thereby strengthening code analysis, execution traces, and execution times. Yet, in the context of WebAssembly, Software Diversification has not been explored.

We present three pioneering tools to the community: CROW, MEWE, and WASM-MUTATE. Each tool is specifically designed to address a unique aspect of Software Diversification. Moreover, these tools synergistically enhance each other. We furnish empirical evidence that Software Diversification is applicable to WebAssembly programs in two distinct manners: Offensive and Defensive Software Diversification. Our investigation into Offensive Software Diversification in WebAssembly reveals potential avenues for improving the detection of WebAssembly malware. In contrast, our experiments in Defensive Software Diversification demonstrate that WebAssembly programs can be strengthened against side-channel attacks, specifically against the Spectre attack.

Keywords: WebAssembly, Software Diversification, Side-Channels, Moving Target Defense

Sammanfattning

LIST OF PAPERS

1. ***WebAssembly Diversification for Malware Evasion***
Javier Cabrera-Arteaga, Tim Toady, Martin Monperrus, Benoit Baudry
Computers & Security, Volume 131, 2023, 17 pages
<https://www.sciencedirect.com/science/article/pii/S0167404823002067>
2. ***Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly***
Javier Cabrera-Arteaga, Nicholas Fitzgerald, Martin Monperrus, Benoit Baudry
Submitted to Computers & Security, under revision, 17 pages
<https://arxiv.org/pdf/2309.07638.pdf>
3. ***Multi-Variant Execution at the Edge***
Javier Cabrera-Arteaga, Pierre Laperdrix, Martin Monperrus, Benoit Baudry
Moving Target Defense (MTD 2022), 12 pages
<https://dl.acm.org/doi/abs/10.1145/3560828.3564007>
4. ***CROW: Code Diversification for WebAssembly***
Javier Cabrera-Arteaga, Orestis Floros, Oscar Vera-Pérez, Benoit Baudry, Martin Monperrus
Measurements, Attacks, and Defenses for the Web (MADWeb 2021), 12 pages
<https://doi.org/10.14722/madweb.2021.23004>
5. ***Superoptimization of WebAssembly Bytecode***
Javier Cabrera-Arteaga, Shrinish Donde, Jian Gu, Orestis Floros, Lucas Satabin, Benoit Baudry, Martin Monperrus
Conference Companion of the 4th International Conference on Art, Science, and Engineering of Programming (Programming 2021), MoreVMs, 4 pages
<https://doi.org/10.1145/3397537.3397567>
6. ***Scalable Comparison of JavaScript V8 Bytecode Traces***
Javier Cabrera-Arteaga, Martin Monperrus, Benoit Baudry
11th ACM SIGPLAN International Workshop on Virtual Machines and Intermediate Languages (SPLASH 2019), 10 pages
<https://doi.org/10.1145/3358504.3361228>

ACKNOWLEDGEMENT

TODO W **TODO** O
TODO Jury
TODO C
TODO F

Contents

List of Papers	iii
Acknowledgement	iv
Contents	1
I Thesis	4
1 Introduction	5
1.1 Predictability in WebAssembly ecosystems	8
1.2 Problems statements	9
1.3 Software Diversification	9
1.4 Summary of research papers	11
2 Background and state of the art	13
2.1 WebAssembly	13
2.1.1 From source code to WebAssembly	14
2.1.2 WebAssembly's binary format	17
2.1.3 WebAssembly's runtime	18
2.1.4 WebAssembly's control-flow	20
2.1.5 Security and Reliability for WebAssembly	21
2.1.6 Open challenges	22
2.2 Software diversification	23
2.2.1 Automatic generation of software variants	23
2.2.2 Equivalence Checking	26
2.2.3 Variants deployment	27
2.2.4 Measuring Software Diversification	28
2.2.5 Offensive or Defensive assessment of diversification	29
2.3 Open challenges for Software Diversification	30

3	Automatic Software Diversification for WebAssembly	32
3.1	CROW: Code Randomization of WebAssembly	33
3.1.1	Enumerative synthesis	34
3.1.2	Constant inferring	35
3.1.3	Exemplifying CROW	36
3.2	MEWE: Multi-variant Execution for WebAssembly	38
3.2.1	Multivariant call graph	39
3.2.2	Exemplifying a Multivariant binary	39
3.3	WASM-MUTATE: Fast and Effective Binary Diversification for WebAssembly	42
3.3.1	WebAssembly Rewriting Rules	43
3.3.2	E-Graphs traversals	44
3.3.3	Exemplifying WASM-MUTATE	45
3.4	Comparing CROW, MEWE, and WASM-MUTATE	47
3.4.1	Security applications	50
4	Assessing Software Diversification for WebAssembly	52
4.1	Offensive Diversification: Malware evasion	52
4.1.1	Cryptojacking defense evasion	53
4.1.2	Methodology	54
4.1.3	Results	56
4.2	Defensive Diversification: Speculative Side-channel protection	60
4.2.1	Threat model: speculative side-channel attacks	61
4.2.2	Methodology	61
4.2.3	Results	63
5	Conclusions and Future Work	69
5.1	Summary of technical contributions	69
5.2	Summary of empirical findings	70
5.3	Future Work	71
	References	73
II	Included papers	87
	WebAssembly Diversification for Malware Evasion	89
	Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly	90
	CROW: Code Diversification for WebAssembly	91

CONTENTS

3

Multi-Variant Execution at the Edge **92**

Superoptimization of WebAssembly Bytecode **93**

Scalable Comparison of JavaScript V8 Bytecode Traces **94**

Part I

Thesis